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Boeing's 737 MAX 8 Disasters

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On October 29, 2018, a nearly new Boeing 737 MAX 8 jet plunged into the Java Sea at 400 miles per hour, killing all 189 people onboard. The sudden and rapid descent of Indonesia's Lion Air Flight 610 commenced at 5,000 feet, just 11 minutes after taking off from Jakarta's Soekarno-Hatta International Airport. Captain Bhavye Suneja and First Officer Harvino, who went by a single name as was common in Indonesia, contacted air traffic control requesting immediate return to Jakarta before losing control of the aircraft. The plane crashed into the sea, "hitting the water with such force that some metal fixtures on the aircraft disintegrated."[1]

The accident initially seemed to be a senseless and anomalous tragedy. Air safety, enforced in large part by the certification process of the Federal Aviation Administration (FAA), was enjoying an exemplary record: Globally, the five-year worldwide average stood at one fatal airliner crash for every 2.5 million to 3 million flights. In the United States, airline safety had reached record levels, with only one passenger fatality in more than 10 years.[2]

Boeing's initial response to the crash focused on Lion Air's airline maintenance procedures and suggested the pilots were at fault.[3] Nonetheless, about eight days later, on November 6, 2018, Boeing issued a bulletin to all 737 MAX 8 and 737 MAX 9 operators indicating that "erroneous angle-of-attack data" could result in "uncommanded nose-down movement of the aircraft and that this action can repeat until the related system is deactivated."[4] The Boeing bulletin provided additional instructions to pilots who might encounter such a dangerous situation. On November 7, 2018, the FAA followed by issuing an Emergency Airworthiness Directive requiring Boeing to revise the operating procedures in its flight manual for the 737 MAX aircraft. Of specific concern was the new Maneuvering Characteristics Augmentation System (MCAS), software designed to prevent the aircraft from stalling by automatically

This case was prepared from public sources by James Quinn, Managing Director, CaseStudy Co., under the supervision of Professor John Sterman.

pushing the nose of the plane down when a high angle of attack (AOA), or nose-up condition, was detected.

Officially, Boeing, including CEO Dennis Muilenburg, repeatedly declared "…the 737 MAX is safe."[5] But, as investigative reporter Peter Robison documented, "Behind the scenes, some of the largest and most respected airlines in the world were screaming that Boeing had hidden the existence of potentially deadly software inside their planes."[6] Internal communications that Boeing handed over to the U.S. Department of Justice and Congressional investigators would later show that the company's own engineers and test pilots had known about the MCAS problem well before the crashes.

After the Lion Air crash, Boeing rushed to redesign MCAS. Boeing Vice President Mike Sinnett initially promised it would take "not a year, but…maybe six weeks-ish" to "tame the system."[7] By March 2019, the revisions were still not completed.

Then, on March 10, 2019, shortly after Ethiopian Airlines Flight 302 took off from Addis Ababa Bole International Airport bound for Nairobi, Kenya, Captain Yared Getachew and First Officer Ahmed Nur Mohammod Nur struggled to ascend at a stable speed.[8] Getachew sent out a distress call, but contact with air traffic control was lost six minutes into the flight. The same model Boeing MAX 8 that had plummeted into the Java Sea crashed near Bishoftu, a town southeast of Addis Ababa. All 157 onboard, hailing from 35 different countries, were killed.[9]

A maelstrom of questions immediately followed, from maintenance crews in Indonesia and Ethiopia, airlines and pilots flying the MAX 8 around the world, Boeing leadership at its Chicago-based headquarters, the FAA and U.S. Congress, and the families of the victims. High-stakes public disputes arose over the root causes of the crashes. U.S. Congressman Sam Graves declared, "Pilots trained in the United States would have been able to handle the emergencies on both jets."[10] Others, however, blamed MCAS and a flawed design process at Boeing. Still others faulted the FAA. A subsequent report by the U.S. Department of Transportation's Inspector General, entitled "Weaknesses in FAA's Certification and Delegation Processes Hindered Its Oversight of the 737 MAX 8," identified "limitations in FAA's guidance and processes that impacted certification…." These included "communication gaps," "management and oversight weaknesses," and "process and structure [that] do not ensure [FAA] personnel are adequately independent."[11]

On March 13, 2019, under pressure from the Indonesian and Ethiopian governments, airlines, pilots, the public, and the families of the 346 dead, the President of the United States Donald Trump ordered the grounding of all 737 MAX aircraft. Several independent review boards were created to identify the root causes of the two crashes and the changes regulators would require Boeing to implement before the aircraft could return to service.

Boeing's best-selling plane remained grounded for 21 months, while customers continued to cancel orders. Through the end of October 2020, Boeing removed 595 MAX orders from the backlog and canceled a further 448, a total loss of 1,043 orders, leaving a backlog of 3,320. Boeing's rival Airbus had a backlog of 5,956 jets for its A320neo family, a direct competitor to the 737 MAX.[12]

On November 18, 2020, just over two years after the Lion Air crash, FAA Administrator Steve Dickson signed an order permitting the 737 MAX to return to commercial service.[13] At the time of Dickson's order, the COVID-19 pandemic had slashed global air travel. Airlines announced plans to return their 737 MAX aircraft to service slowly.

Yet major questions remained as passengers once again began flying on the MAX 8, which Boeing rebranded the 737-8.[14] What role, if any, did company engineers play in causing the two catastrophes? What about their managers? Their test pilots? What role did Boeing's CEO, board, and other senior leaders play in shaping the processes, procedures, and corporate culture that may have set the stage for the disasters? Why didn't the FAA detect the flaws in the design before allowing the 737 MAX 8 to enter service? How could future disasters be prevented?

Air Safety

Over many decades, commercial aviation had become much safer. Technical innovation in engines, airframes, cockpit instrumentation, communications, software, and control systems—together with better procedures and stronger regulations governing aircraft testing, certification, pilot training, operations, and air traffic control—all contributed to improving safety.

Measured by accidents per passenger miles flown, the improvements were impressive. In 2018, the National Safety Council (NSC) reported only 1 death per 100 million passenger miles on scheduled airlines in the U.S. **Exhibit 1** shows U.S. commercial aviation accidents, 1975–2018.

However, the number of flights, flight hours, and passenger miles traveled per year all exploded as people around the world became more affluent and average fares fell. From 2010 to 2019 (the year before COVID-19 drastically cut airline travel), passengers carried by scheduled commercial air traffic grew from 2.7 billion to 4.5 billion worldwide, and total flight miles grew from less than 3.1 trillion to nearly 5.4 trillion passenger miles.[15] The industry formed a complex web with more than 1,400 scheduled airlines, 26,000 aircraft, 3,900 airports, 173 air navigation centers, 360,000 pilots, and 86,000 air traffic controllers.[16]

The growth in air travel meant that the accident rate did not fall as much as data on accident per flight or per passenger mile suggested. Between 1959 and 2008, 33.8 commercial jet accidents per year occurred worldwide, 35% of which involved fatalities. Between 2009 and 2018, 41.4 accidents per year occurred, 13% of which were fatal.[17]

The root causes of accidents remained a hotly contested topic. Human error was often the go-to explanation. In a 2006 study, the FAA noted, "Although percentages vary, most would agree that somewhere between 60%–80% of aviation accidents are due, at least in part, to human error."[18]

Safety experts, however, argued that most human errors were the result of poorly designed equipment and systems.[19] In addition to focusing on "personal safety"—roughly speaking, admonishing people to be careful—designers focused on increasing "process safety"—designing an intrinsically safe system that minimized opportunities for and consequences of human error. As safety expert and psychologist James Reason noted, "Though we cannot change the human condition, we can change the conditions under which humans work."[20]

The Boeing Company

Incorporated in 1916 by timber baron William E. Boeing, the company's first contracts were with the U.S. Navy, for which Boeing produced seaplanes, patrol flying boats, and torpedo bombers. During World War II, Boeing produced nearly 100,000 aircraft, including the famous B-17 Flying Fortress. Between 1942 and 1944, the company ramped up production from 60 to 362 B-17s per month. After the war, Boeing went on to develop the B-52 Stratofortress strategic bomber and other critical military aircraft. Boeing also developed the nation's first commercial jet airliner, the Boeing 707, delivering the first one to Pan Am to serve a transatlantic route.

Boeing became the preeminent player in the commercial airline industry. Author John Newhouse wrote:

> Back in the 1970s and early 1980s, four companies divided the turbulent business of making and selling passenger airplanes. One of them, the Boeing Company, was dominant. The other two big American players—the Lockheed Aircraft Corporation and the McDonnell Douglas Corporation—labored in the wake of their own mistakes. Lockheed's were terminal, and McDonnell Douglas, known in the trade as McDac, hadn't come to terms with reality. The reality was that a small European company called Airbus Industrie, generally known only as Airbus, had abruptly become not just a player but a mortal threat. Simply put, Airbus was eating McDac's lunch.
>
> In the 1980s, …Boeing was universally judged one of America's best and most admired companies, partly because its sales abroad of large commercial airplanes were the country's biggest export, and partly because it had learned to build these airplanes better, faster, and cheaper than anyone else had done. 'World-class' was Boeing's lofty but accurate characterization of itself.[21]

By the end of 1990, Boeing held 62% of the commerical airline market, with sales of $20.3 billion and earnings of $973 million.[22] McDonnell Douglas (23%) and Airbus (15%) trailed far behind.[23]

Thornton "T" Wilson

One of Boeing's legendary leaders, Thornton "T" Wilson, was credited with shaping much of the company's success. With a bachelor of science degree in aeronautical engineering from Iowa State University and a master of science degree from California Institute of Technology, Wilson joined the company in 1943 to work on its bomber programs. He became president of Boeing in 1968, CEO in 1969, and chairman in 1972. A hands-on manager who had worked on the factory floor, Wilson understood every blue-collar job involved in the production process, and engaged closely with employees at all levels. Newhouse commented: "Wilson would sit down with factory workers at lunch in the cafeteria and find out what was going on in their various operations; and then if it was advisable, he would take up what he'd learned with the relevant managers." As one former executived noted, "He ran the company. It did not run him."[24]

During Wilson's leadership and soon after his retirement in 1986, Boeing became the market leader in commercial aircraft, defense, space, and security systems. Company engineers took on some of the most challenging work in the industry, including high-visibility U.S. government contracts. In 1980, Boeing initiated a study of the space station concept with NASA. In 1982, Boeing engineers designed a solar power satellite system capable of providing power to millions of homes.[25] In 1988, the company delivered to the U.S. Army the first Avenger "air defense system," one of several Cold War innovations. And, in 1994, Boeing Computer Services won the contract to design software for the Space Shuttle Program. Meanwhile, four years earlier, the Boeing 737 became the best-selling jetliner in the world.

During Wilson's tenure, it was common for employees to spend their entire career at Boeing, as was the case with Wilson himself, forging a "social contract" between workers and the company. Boeing researchers Leon Grunberg and Sarah Moore summarized the company ethos:

> Management of the company was anchored in loyalty and promoting through the ranks. Indeed, so-called Heritage Boeing employees were extremely proud of building innovative, safe, quality products, such as the 707 and 747, airplanes that set the global standard in commercial aviation when launched. Executives told their employees—and the employees believed—that they were number one in the world, as indeed they were until Airbus gradually ate into Boeing's market share and achieved parity in deliveries in the early 2000s.[26]

Years after retiring from Boeing, many employees reflected nostalgically on the Boeing family atmosphere, where a deep commitment to quality engineering and pride in the work carried the day. Grunberg and Moore explained:

> Boeing offered lifelong employment and the promise of a meaningful career. Opportunities for growth and promotion were endless, and despite the cyclical nature of the industry and the accompanying layoffs, one could work at Boeing for life, as could members of one's family. It was

commonplace for one's parents, grandparents, children, siblings, aunts, and uncles to work for the company.[27]

While the company employed thousands of people in the state of Washington's Puget Sound region, many recalled feeling like they were members of a "Boeing family." As one longtime engineer said, "I've been to weddings. I've been to funerals and Christmas parties. I've got friends I've done dog sitting for. Our families still get together." The emotional ties employees had with Boeing went beyond coworkers and supervisors and included the airplanes they built and the buildings in which they worked.[28]

Acquiring McDonnell Douglas

When I say I changed the culture of Boeing, that was the intent, so it's run like a business rather than a great engineering firm. It is a great engineering firm, but people invest in a company because they want to make money.

– Harry Stonecipher, 2004, former president and CEO of McDonnell Douglas and then Boeing[29]

In December 1996, Boeing announced its intention to purchase long-time rival McDonnell Douglas in a stock swap valued at $13.3 billion. It was the 10th-largest U.S. merger at that time and the largest in the aerospace industry. Under the terms of the agreement, 0.65 Boeing shares were exchanged for each McDonnell Douglas share. The implied value of $62.89 per share represented a 21% premium on McDonell's closing price of $52 when the deal closed on July 31, 1997.

On its face, joining the two companies, which analysts estimated would yield in excess of $48 billion in 1997 revenue—$28 billion from Boeing and $20 billion from McDonnell Douglas—would bring together complementary product lines and internal capabilities, while helping to mitigate market risk for each. "We've looked very carefully at all of our programs," said Philip Condit, then Boeing's president and CEO. "We believe that dramatically they are complementary. There are some overlaps, but they're very, very minor."[30]

Whereas Wilson knew many frontline employees by name and often met with them, Boeing's headquarters and senior management were moved to Chicago, about 2,000 miles from the commercial aircraft division. The reporting structure changed so that top engineers reported first to business leaders in each division and second to the chief engineer. In the years following the merger, many longtime Boeing employees lamented what they perceived as a fundamental change from "an engineering and 'family' culture to a 'team' and shareholder value culture."[31]

Other changes included the computerization of parts ordering, a shift to lean manufacturing to reduce cycle times, increased use of outsourcing and global partnering—and approximately 50,000 layoffs between 1999 and 2003.[32]

Some observers noted growing conflict between the engineering culture that Wilson had built with a "bean counter" approach that emerged among many of his successors, particularly after the merger. "Boeing's critics, in-house as well as external, complain about a heavy presence of inexperienced business-school types and too little listening to the airline market," said author John Newhouse.[33]

Kyle Smith, a business operations and corporate consultant with 30 years of experience at Boeing, commented on the labor-management dynamic following the merger:

> So you have a workforce that is highly disillusioned, that feels that leadership is out of touch. Management deals with that by hiding and by being increasingly authoritarian. A culture of fear is the only way they have of maintaining control. And it's all done in an environment of encouraging people to tell management what they think, which is absolutely the opposite of what management actually wants them to do. So you get all of these double messages and double binds that you're putting the workforce in, of saying we want your input but when we get it you're punished or held back because of it. We want your input, but when you give it, you're not a team player, because team players only give us things that make us feel better.[34]

In the past, Boeing engineers with safety concerns could and would raise them even if doing so held up progress until the issue was resolved.[35] Carrie Conway was a 62-year-old hourly worker in 2012 with 26 years of experience with Boeing when she noted the difficulty she faced in presenting quality issues to her boss while working on the 787 family of aircraft:

> One day I'm working, and my lead brought all the parts out of storage. They were all wrapped up in a paper, brown bag. This was a Monday morning, so all the tables were stacked with the necessary parts to do whatever we were working on. So I started unwrapping mine, and you could see chips in it, little tiny holes. And there were areas where you could see corrosion—corrosion has a different look to it. So the first part I took to my lead, and I said, 'Look at this.' He said, 'Oh, can't use that.' Well, it took four parts to get one that I could use. When the inspector came in, I called him over—I'd saved one of them. I said, 'I want you to look at this part,' and he goes, 'Well, that's not acceptable,' and I said, 'Well, we got a whole warehouse full of them, you know. I had to get to the fourth part to find an acceptable one.'
>
> He went into the warehouse, started checking all these parts, and he came back and stopped production. He figured about two-thirds of this order was pitted and corroded. Before the day was over, his boss and my boss were standing on one side of the table. My inspector and I were standing on the other side of the table. My boss was telling me I have to use these parts, and both of us said, 'No, we're not doing that.' It took months. I'm not sure even when, because I ended up getting transferred out of the building over it.[36]

Enter Airbus

In the 1960s, European nations and aircraft companies felt the need to respond to U.S. industry dominance in commerical aviation. Under Anglo-French-German leadership, many smaller European aircraft makers were consolidated, and a new player entered the market: Airbus Industrie. Other European nations joined in, with design and assembly spread across the Continent. The first Airbus, the A300, was designed to be more efficient and less expensive than similar medium-sized American jets, including Boeing's. Yet Airbus had a rocky start. The first A300 flew in 1972, but by 1979 Airbus had only delivered 26 aircraft, less than a tenth of Boeing's 286 deliveries.

Nevertheless, Airbus steadily grew, expanding its product line and sales. Soon Boeing and Airbus dominated the industry in a global duopoly, with smaller niche players such as Bombardier and Embraer trailing behind.

In 1999, Boeing still supplied the majority of the market, delivering 573 new jets, compared to Airbus's 294. But Airbus continued to build its product line and organizational, engineering, operational, and marketing capabilities, successfully acquiring new customers. Airbus continued to cut into Boeing's market share and in 2003 delivered 305 new jets, outpacing Boeing's deliveries for the first time. **Exhibit 2** shows aircraft deliveries and orders for Boeing and Airbus through 2019.

The 737 vs. the A320

Boeing and Airbus competed for the same customers and the same routes in every region of the world. Each offered a family of aircraft spanning the entire market. Competition was intense. A major battle involved Boeing's 737 and Airbus's A320 models. Author of *Boeing versus Airbus* John Newhouse explained:

> The low end of the market is covered by two single-aisle airplanes, Boeing's 737 and Airbus's A320. They are roughly the same size, seating up to 190 people. Both are exceptionally successful, having exceeded the most optimistic forecasts of their respective companies. The 737 is older and has been steadily improved over the years. But the A320, a newer, slightly larger, and more comfortable aircraft, is outselling the 737, not least in the low-cost market Boeing had monopolized. [37]

In December 2004, with orders surging for Airbus's A320s, Boeing shook up its sales force, replacing its head of sales.[38]

The success of the A320 raised the stakes in Boeing's battle with Airbus, including the decision on whether to develop and build a new aircraft. Newhouse wrote:

> The decision to build a new LCA (Large Commercial Aircraft) alerts boards of directors and shareholders to impending deficits, big ones. Indeed, the costs of any such venture can amount to

> betting the company, literally. A single deal with one airline can determine the fate of an airplane on which billions of dollars have been invested. And the returns, if any, lie far ahead.[39]

The 737 MAX Program

Boeing's products cover the entire commercial market. The 737 family had an average range of 4,000 miles and seating capacity of approximately 130 to 220 passengers. **Exhibit 3** shows the Boeing 737 aircraft family from 1967 to 2017. Other families consisted of larger planes with longer ranges. Prices varied from $89 million for the 737-700 to $442 million for the 777-9 **(Exhibit 4)**. The average price of the 737 MAX 8 was $122 million.[40]

The Boeing Commercial Airplanes (BCA) division launched the 737 MAX project in August 2011. Within the 737 MAX family, the MAX 8 was the first to market, with the first delivery in May 2017. The schedule was compressed compared to other development projects. **Exhibit 5** shows select Boeing Commercial Airplanes "Go Ahead" and "Initial Delivery" schedules for several aircraft development projects. **Exhibit 6** shows a timeline for the MAX 8 project including FAA certification actions.

The 737 MAX family came to market with high expectations for Boeing's sales and profits, and those expectations were soon exceeded. In 2017, Boeing led the industry in deliveries for the sixth consecutive year, with the 737 MAX family earning the distinction of "the fastest-selling airplane in Boeing history."[41] Boeing featured the MAX in its 2018 Annual Report:

> The 737 is designed to be 14 percent more fuel efficient than today's most efficient Next-Generation 737s [launched in 1997] and 20 percent more fuel efficient than the original Next-Generation 737s when they entered service. With new CFM International LEAP-1B engines, a more efficient structural design, advanced technology winglets, and lower maintenance requirements, the entire MAX family has been designed to offer exceptional performance, flexibility, and efficiency.[42]
>
> The 737 family continues to exceed expectations in the single-aisle market, with 745 net new orders received and a company record of 529 airplanes delivered in 2017. Our 737 backlog now stands at more than 4,600 airplanes.[43]

Exhibits 7 and **8** present Boeing's financial performance during this period.

Anatomy of Two Disasters

In 2010, Airbus announced the development of the A320neo, a fuel-efficient plane that quickly captured the attention of many carriers. In early 2011, Boeing's CEO, W. James McNerney, received a phone call from the head of American Airlines indicating that the company, a long-time customer, was considering placing an order for hundreds of A320neo airplanes from Airbus.[44] For Boeing, the stakes were high. The American Airlines account represented billions in future revenue, and the loss of such

a prominent customer could threaten Boeing's market-share dominance. At the time, Boeing was considering the development of a brand-new passenger airplane, with an expected development cycle time of 10 years. To respond to the threat, McNerney and his team scrapped the plan to develop a new plane, opting instead to update the 737. McNerney told a group of Wall Street analysts: "All of us have gotten religion. Every 25 years a big moonshot—accumulating technologies and taking risks on some additional ones and then producing a 707 or a 787—that's the wrong way to pursue this business… . The more-for-less world will not let you pursue moonshots."[45]

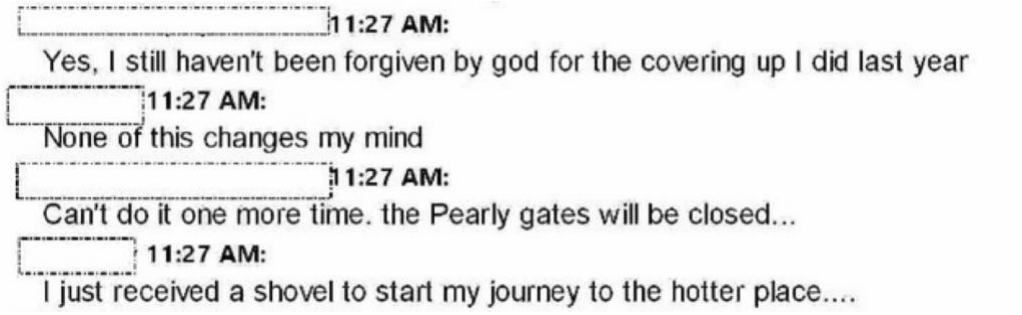
The Boeing team hustled into action, launching the 737 MAX project three months after learning of American Airlines' potential defection. An engineer on the 737 MAX flight control team noted, "[The company wasn't] going to stand by and let Airbus steal market share."[46] Months behind Airbus, Boeing found itself in catch-up mode. As *The New York Times* reported, "The pace of work on the 737 MAX was frenetic. … Engineers were pushed to submit technical drawings and designs at roughly double the normal pace. Facing tight deadlines and strict budgets, managers quickly pulled workers from other departments when someone left the MAX project."[47] As a Boeing engineer said, "The timeline was extremely compressed. It was just go, go, go."[48] Management installed a countdown clock in a conference room where program meetings were held as a constant reminder of "the value of a day."[49]

According to a designer who worked on the 737 MAX flight controls, the design team at times found itself producing 16 technical drawings a week—double the normal pace.[50] A technician who assembled wiring on the 737 MAX reported that many of the blueprints designers provided him were uncharacteristically sloppy, reporting that management told him "instructions for wiring would be cleaned up later in the process."[51] Mark Rabin, who worked in a flight test group that supported the 737 MAX, noted, "It was a climate that didn't reward people willing to buck managers."[52]

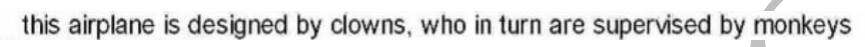
Behind the scenes, however, employees working on the 737 MAX shared, among themselves, concerns about the hurried timeline and resulting slip-shod work. Some of their misgivings were revealed after Boeing turned over internal texts and emails to the U.S. Department of Justice and Congressional investigators.[53] In an email exchange in May 2018, employees working on the 737 MAX lamented the pressure they were under to quickly approve a large number of open design review issues (DRs):[54]

[redacted] **11:19 AM:**
They are desperate for a go
[redacted] **11:19 AM:**
No kidding
[redacted] **11:19 AM:**
Every system is impacted by DRs - how do you work around all DRs?

The conversation turned darker:



Prior to the crashes, employees expressed their disdain for the way in which they perceived management was undermining quality and safety. As one wrote,[55]



The Origin of MCAS

To compete head-to-head with Airbus's 320, the 737 MAX needed larger, more powerful, and more efficient engines. Boeing chose a new engine: the CFM LEAP-1B. However, as an analyst explained, the new engine required a number of critical design changes:

> Because they're bigger, and because the 737 sits so low to the ground (a deliberate 737 design choice to let it serve small airports with limited ground equipment), Boeing moved the engines slightly forward and raised them higher under the wing. (If you place an engine too close to the ground, it can suck in debris while the plane is taxiing.) That change allowed Boeing to accommodate the engines without completely redesigning the 737 fuselage—a fuselage that hasn't changed much in 50 years.[56]

Exhibit 9 compares the engine size and placement for the 737 NG and 737 MAX.

In 2012, early in the design phase, engineers gathered at Boeing's transonic wind tunnel in Seattle to test the jet's aerodynamics. Using a scale model with a wingspan comparable to that of an eagle[57], they discovered that the plane's nose tended to pitch up during a specific "extreme maneuver."[58] As MIT aeronautics professor R. John Hansman explained, "As I understand it, at high angles of attack the nacelles—which are the tube-shaped structures around the [engine] fans—create aerodynamic lift. Because the engines are further forward, the lift tends to push the nose up—causing the angle of attack to increase further. This reinforces itself and results in a pitch-up tendency which if not corrected can result in a stall."[59] If that self-reinforcing feedback caused the nose to pitch up high enough to cause the aircraft to stall, the result could be catastrophic.

The engineers worked to devise a countermeasure to what they viewed as a highly unlikely occurrence and, after several attempts, developed new software intended to respond to the problem automatically.

The Maneuvering Characteristics Augmentation System or MCAS was originally designed to activate only if the flight management computer detected both a high angle of attack (AOA) and high vertical G-force. A high AOA indicated the nose was pitched up, and high G-force meant it was accelerating upward. If triggered, MCAS would automatically move the horizontal stabilizer (at the tail of the aircraft) to push the nose of the plane down (**Exhibit 10**). MCAS was created as a safety system intended to correct what was originally believed to be a rare, but potentially dangerous, pitch-up condition without requiring any pilot action.

Based on tests conducted during the design phase, engineers believed that the potential runaway pitch-up condition would only occur during certain high-speed maneuvers. Consequently, MCAS was originally designed to move the stabilizer 0.6 degrees over about 10 seconds, enough, at high speed, to bring the nose down to a safe trim position. Further testing, however, revealed that the same pitch-up could also happen at low speeds.[60] To address this discovery, MCAS was reprogrammed to operate at low speeds such as after takeoff and during the climb to cruising altitude. Because lower speeds required more aggressive control actions, the modified software enabled MCAS to move the stabilizer down 2.5 degrees in about 10 seconds, more than four times faster. Additionally, low-speed maneuvers would not generate high G-forces, so the G-force condition required to engage MCAS was dropped.[61] MCAS was designed to trigger again if the high AOA condition was still detected after five seconds.

Redundancy Made Optional

Engineers build redundancy into their systems to avoid "single points of failure," in which the failure of a single component causes an accident or stops the system from operating. Redundancy is standard practice for critical components and systems in commercial aircraft. The revised MCAS, which no longer required both a high AOA and high G-force to be triggered, now depended only on AOA data, provided by AOA sensors, small vanes located near the nose of the aircraft. The sensors, however, can go out of alignment or fail altogether due to mechanical and electrical faults, improper maintenance, icing, bird strikes, and other causes. In 2019, CNN reported that since 2004, the FAA had received at least 216 reports of AOA sensors failing or having to be repaired, replaced, or adjusted. The FAA had also issued two directives involving AOA sensors for various Boeing aircraft models before the 737 MAX was released.[62]

To provide redundancy, the 737 MAX had two AOA sensors, one on each side of the nose. (The Airbus 320 and some other Boeing aircraft have three sensors to provide double redundancy.) However, MCAS was designed to use data from only one of the sensors (alternating after each flight). Relying on just one sensor created a single point of failure hazard. To address the possibility that the single sensor in use failed or gave erroneous readings, the designers created a cockpit display showing the readings

from both AOA sensors. The display was programmed to activate a cockpit "AOA DISAGREE" alert if the readings differed by more than a few degrees (**Exhibit 11**).

However, whereas MCAS was activated automatically, without pilot action, the cockpit crew would have to notice and act on an AOA DISAGREE alert. Further, the AOA indicator and disagree alert were not standard equipment on the 737 MAX, although the AOA indicator had been on earlier models. Boeing offered them as "add ons" at additional cost. Neither feature was required by regulators. Lion Air, Ethiopian Airlines, and other carriers, including Southwest Airlines, had chosen not to pay extra for these features. According to government and industry officials, "Boeing Co. didn't tell Southwest Airlines Co. and other carriers when they began flying its 737 MAX jets that a safety feature found on earlier models that warns pilots about malfunctioning sensors had been deactivated."[63]

Boeing issued an explanation:

> The disagree alert was intended to be a standard, stand-alone feature on MAX airplanes. However, the disagree alert was not operable on all airplanes because the feature was not activated as intended.
>
> The disagree alert was tied or linked into the angle of attack indicator, which is an optional feature on the MAX. Unless an airline opted for the angle of attack indicator, the disagree alert was not operable.[64]

Because MCAS relied on data from only one of the AOA sensors, 737 MAX planes that did not have the optional AOA indicator and disagree alert would not directly report a problem with the sensor. In fact, as documented in the 322-page report on the Lion Air crash issues by Indonesia's Aviation Safety Agency:

> The sensor, provided second-hand by a Florida-based company called Xtra Aerospace, was not calibrated correctly nor did Lion Air maintenance crews detect the error when they installed the sensor the day before the crash (31 pages were missing from the aircraft's maintenance log at the time). The fault in the sensor meant that it was feeding incorrect information to MCAS.
>
> The 737 MAX has a warning light that would have shown that the faulty sensor was disagreeing with the working sensor on the other side of the aircraft's nose. But a software bug meant that the warning light was working only if Lion Air purchased a package of equipment Boeing sold only as an option.[65]

FAA Certification

As Boeing engineers worked night and day to ready the 737 MAX for production, others took steps, at the direction of their managers, to get the FAA to fast-track the certification process. The formal certification process for the 737 MAX 8 began in 2012. Under FAA protocols, "only the significant

differences" between the 737 MAX 8 and the previous model required certification.[66] Boeing argued that the differences between the 737 MAX and the previous 737 NGs (next generation) were not significant and positioned MCAS as a minor addition to existing speed trim functionality, as revealed in minutes of a meeting on June 7, 2013:[67]

07-JUN-2013 ANALYSIS [redacted] [redacted] 07-JUN-2013 08:29:23
6/7/13 Meeting Minutes:
1) GTTA left the name as MCAS but treated as analogous function as a speed trim type function.
2) If we emphasize MCAS is a new function there may be a greater certification and training impact.
3) Treat as an addition to Speed Trim.
4) Externally we would communicate it is an addition to Speed Trim.
5) Internally continue using the acronym MCAS (within variable names etc).
6) Work with AR on certification perspective to ensure this strategy is acceptable.
7) Make sure EASA Fam Tech presentation is consistent with intent that MCAS is an addition to Speed Trim.

07-JUN-2013 PROP_RES [redacted] [redacted] 07-JUN-2013 12:18:39
After speaking with the Autoflight AR, concurrence was provided that we can continue to use the MCAS nomenclature internally (variable names, etc) while still considering MCAS to be an addition to the Speed Trim function. This will allow us to maintain the MCAS nomenclatue while not driving additional work due to training impacts and maintenance manual expansions.

Boeing succeeded in positioning MCAS as a minor modification to earlier models, as detailed in a 2020 report by the U.S. Department of Transportation Office of the Inspector General:

> Early in the process, Boeing included limited information in initial briefings to FAA on the MAX's flight control software, MCAS, which subsequently has been cited as a contributing or potentially contributing factor in both accidents. However, Boeing presented the software as a modification to the existing speed trim system that would only activate under certain limited conditions. As such, MCAS was not an area of emphasis in FAA's certification efforts and therefore did not receive a more detailed review or discussion between FAA engineers and Boeing. Instead, FAA focused its efforts on areas it identified as potentially high risk, such as the aircraft's larger engines, fly-by-wire spoilers, and landing gear changes. As a result, FAA was not well positioned to mitigate any risks related to MCAS.[68]

Meanwhile, in 2016, about one-third of the way through testing, Boeing engineers increased the stabilizer nose-down deflection each time MCAS was activated at low speeds, from 0.6 degrees to 2.5 degrees, and removed the G-force condition initially required to trigger MCAS. An analyst explained: "On the stabilizer, maximum nose down is about 4.7 degrees away from level flight. So with the new

increased authority to move the stabilizer, just a couple of iterations of the system could push it to that maximum."[69]

Mark Forkner, chief technical pilot for the 737 MAX, was apparently not informed about these changes, but discovered them in the flight simulator, complaining about it to a colleague on November 16, 2016:[70]

Mark Forkner 6:50 PM:
Oh shocker alerT!
MCAS is now active down to M .2
It's running rampant in the sim on me
at least that's what Vince thinks is happening
Gustavsson, Patrik H 6:51 PM:
Oh great, that means we have to update the speed trim descritption in vol 2
Mark Forkner 6:51 PM:
so I basically lied to the regulators (unknowingly)
Gustavsson, Patrik H 6:51 PM:
it wasnt a lie, no one told us that was the case
Mark Forkner 6:51 PM:
I'm levelling off at like 4000 ft, 230 knots and the plane is trimming itself like craxy
I'm like, WHAT?

According to the Inspector General's report, Boeing failed to report the MCAS changes to the FAA during the certification process:

> During this timeframe, Boeing also began modifying MCAS as a result of flight testing, including significantly increasing MCAS's ability to lower the aircraft's nose automatically under certain conditions. However, Boeing did not submit certification documents to FAA detailing the change. FAA flight test personnel were aware of this change, but key FAA certification engineers and personnel responsible for approving the level of airline pilot training told us they were unaware of the revision to MCAS. Boeing did not communicate to FAA the formal safety risk assessments related to MCAS until November 2016 and January 2017, more than 4 years into the 5-year certification process… . Moreover, Boeing's safety analysis did not assess system-level safety risks as catastrophic; thus, Boeing designed MCAS to rely on data from a single aircraft sensor rather than including redundancy, which would have reduced risk.[71]

Pilot Training

Boeing also sought to avoid the need for extensive pilot training, in particular training in a 737 MAX flight simulator. Simulation training was expensive and time consuming for airlines, and Boeing feared it might limit sales. One engineer, who helped design the 737 MAX cockpit and spent 19 years at Boeing, said the company set a ground rule for engineers: "Limit changes to hopefully avert a requirement that pilots spend time training in a flight simulator before flying the MAX. Any designs we created could not drive any new training that required a simulator. That was a first."[72]

Throughout the project, Boeing employees worked to persuade the FAA, their counterparts in other nations, and customer airlines that MCAS and other changes were minor so as to avoid a requirement for simulator training for experienced 737 pilots. Forkner repeatedly argued that there were no significant differences between the 737 MAX and the prior 737 NG. He maintained that computer-based training (CBT) was sufficient. As he wrote in an email to a customer:[73]

From: [redacted]@boeing.com>
Sent: Tuesday, June 6, 2017 11:01:40 AM
To: [redacted] **Boeing Employee**
Cc: [redacted]
Subject: RE: MAX LEVEL B DIFFERNCES SOLUTION

[redacted]

There is absolutely no reason to require your pilots to require a MAX simulator to begin flying the MAX. Once the engines are started, there is only one difference between NG and MAX procedurally, and that is that there is no OFF position of the gear handle. Boeing does not understand what is to be gained by a 3 hour simulator session, when the procedures are essentially the same.
Perhaps we should discuss at your earliest opportunity. The FAA, EASA, Transport Canada, China, Malaysia, and Argentinia authorities have all accepted the CBT requirement as the only training needed to begin flying the MAX. I'd be happy to share the operational differences presentation with you, to help you understand that a MAX simulator is both impractical and unnecessary for your pilots.
Please let me know when would be the best time to have a webex discussion.
Thank you

[redacted]
737 Chief Technical Pilot
[redacted]
BOEING

In their efforts to persuade customers and regulators that simulation training on the 737 MAX wasn't necessary and that CBT would be sufficient, Forkner and others referred to using "Jedi mind tricks."[i] On June 7, 2017, Forkner wrote:[74]

Looks like my jedi mind trick worked again!

These are not the droids you're looking for....

[i] As defined on the StarWars.com website, a Jedi mind trick is when an experienced Jedi (heroic protagonists of the Star Wars franchise) uses the Force to implant a suggestion in the minds of those they encounter, encouraging them to comply with the Jedi's wishes.

On December 12, 2017, more Jedi references were made. The DGCA referred to the Directorate General of Civil Aviation in India:[75]

I just jedi mind tricked this fools.

I should be given $1000 every time I take one of these calls

I save this company a sick amount of $$$$

[redacted] 9:31 PM:
what did you convince them of?

[redacted] 9:31 PM:
to simply produce an email from me to the DGCA that states all the airlines and regulators that accept only the MAX CBT

to make them feel stupid about trying to require any additional training requirements

[redacted] 9:33 PM:
well done, i give you a raise. all you need to do is go to [redacted] and accept it.

Boeing proposed and obtained a "Level B" training plan requiring only CBT for pilots already certified on prior 737s. As described in the Inspector General's report:

> In 2016, FAA and Boeing began certification flight testing to determine the aircraft's compliance with FAA's requirements. In addition, FAA's Flight Standards Service conducted separate tests and subsequently approved a training plan proposed by Boeing—known as Level B training—for 737 MAX pilots who were already qualified to fly the Boeing 737-800. This outcome aligned with Boeing's overarching goal of achieving a common type rating[ii] for pilots moving from the NG series to the MAX and keeping costs down by avoiding simulator training for 737 MAX pilots. Pilot response to automated MCAS activation was not included in the required training. In March 2017, FAA issued an ATC[iii] to Boeing for the 737 MAX 8, which began flying passengers later that year.[76]

Inside Boeing, provisional FAA approval of Level B training was cause for celebration by at least one member of the product marketing team, who emailed Mark Forkner and others on August 16, 2016:[77]

[ii] A type rating is an endorsement on the pilot certificate indicating that the pilot has completed the required training and testing for a specific make, type, and/or series of aircraft (for example the Boeing 747-400). From https://www.oig.dot.gov/sites/default/files/F.A.A.%20Oversight%20of%20Boeing%20737%20MAX%20Certification%20Timeline%20Final%20Report.pdf, accessed December 17, 2020.

[iii] An Amended Type Certificate (ATC) is issued for aircraft deemed to be "derivatives of already-certificated aircraft."

From: Boeing Employee
Sent: Tuesday, August 16, 2016 3:43 PM
To: @boeing.com>; @boeing.com>
Cc: @boeing.com>; boeing.com>; @boeing.com>; @boeing.com>; @boeing.com>; @boeing.com>; @boeing.com>
Subject: RE: MAX Differences Training approved at Level B!!!!!

Hey,

RIGHT ON!! So the devil is in the details: Do we have 1-day of CBT endorsed and in stone by FAA (AEG)? And, just to confirm, there are absolutely no formal checks? And, no functional currency issues between NG and MAX . . . you can be away from an NG for 30-years and still be able to jump into a MAX? LOVE IT!!

Absent simulator training, 737 MAX pilots were limited to learning about important differences between the 737 MAX and legacy 737 aircraft through "about an hour's worth of iPad-based training," reported one analyst.[78] Some employees believed the training was inadequate and shared their concerns with one another, as in this February 2018 email exchange:[79]

03:50:
Honesty is the only way in this job - integrity when lives are on the line on the aircraft and training programs shouldn't be taken with a pinch of salt. Would you put your family on a MAX simulator trained aircraft?
I wouldn't
03:51:
No

Many pilots interviewed in the wake of the accidents, including 737 MAX 8 pilots from Southwest Airlines, expressed no prior knowledge of MCAS or related procedures required to manage or override the system should it be activated. "We flat out deserve to know what is in our airplanes," said a member of the Allied Pilots Association.[80]

The Indonesian National Transportation Safety Committee (NTSC), which was investigating the Lion Air crash, determined that inadequate training and flight manual descriptions were contributing factors to the accidents. The reported concluded, "The absence of guidance on MCAS or more detailed use of trim in the flight manuals and in-flight crew training made it more difficult for flight crews to properly respond."[81]

Aftermath

In April 2019, shortly after the crash of Ethiopian Airlines Flight 302, CEO Muilenburg established a committee at the board level to review the company's aircraft design and development policies and processes. The recommendations reportedly included flipping the reporting structure so that senior engineers would report "primarily" to Boeing's chief engineer, and "secondarily" to business unit leaders. The committee also recommended the creation of a new safety group to ensure that the company's various efforts had adequate independence and were working together and sharing

information effectively. The new group would report to senior Boeing leadership, as well as to a new permanent board committee focused on aerospace safety. And, consistent with the systems approach to safety, the committee recommended that Boeing re-examine cockpit design and operation to ensure that new Boeing planes were designed for the next generation of pilots, including those with less training.[82]

In May 2019, CNN reported that Boeing proposed that pilots attend a CBT program before they resumed flying the 737 MAX. The program did not involve hands-on simulator training.[83] By January 2020, however, Boeing reversed course and began recommending that pilots undergo simulator training before they resumed flying the 737 MAX.[84] In November, the FAA issued new regulations requiring special training, including ground and flight training in a full flight simulator for pilots operating the 737 MAX.[85]

Multiple investigations including criminal inquiries followed the crashes. On October 19, 2019, the first anniversary of the Lion Air crash, CEO Muilenburg, who had just been removed as chair of Boeing's board, was called to testify before a U.S. Senate panel. Families of the passengers were in attendance, holding up photos of those who had been killed. Asked why Boeing did not ground the 737 MAX after the Lion Air crash, Muilenburg responded, "If we could go back, we would make a different decision."[86]

The following week, Boeing fired Kevin McAllister, CEO of Boeing Commercial Airplanes. Then, in December 2019, Boeing's board fired CEO Muilenburg, replacing him with David Calhoun, who had been named chair of the board following Muilenburg's removal. Calhoun was a veteran of General Electric and had served on Boeing's board since 2009.

FAA Safety Personnel Survey

In August 2020, the media reported on results from a survey of FAA safety personnel. Respondents indicated they "faced 'strong' external pressure from industry." The survey quoted one employee as saying that the message was, "Don't rock the boat with Boeing." Nearly half of survey respondents disagreed that the FAA "makes data-driven decisions on safety regardless of external pressure." Agency employees stated that they could be "over-powered in meetings with industry." One employee said: "It feels like we are showing up to a knife fight with Nerf weapons. It is a challenge to be an equal match with Boeing in the meetings/conversations."[87]

When the results became public, the FAA's Ali Bahrami, an associate administrator for safety, told his team he was "troubled by the findings and would work to rebuild trust."[88] Earlier in his career, Bahrami led the FAA's Transport Airplane Directorate in Seattle, and, reportedly, pursued "the FAA's new business mantra with gusto." When FAA "specialists raised technical issues, they'd be told to stand down—often by Bahrami himself."[89] Under pressure from many in Congress, victims' families, FAA staff, and others, Bahrami announced his retirement in June 2021.

Financial and Reputational Damage

Estimates of the financial and reputational damage to Boeing, its shareholders, employees, suppliers, and the U.S. and global economy varied. One concluded that Boeing faced over $21 billion in direct costs and $67 billion in lost sales of 1,200 aircraft. Direct costs included:

- $8.6 billion in compensation to customers for having their aircraft grounded;
- $5 billion for unusual costs of production;
- $6.3 billion for increased costs of the 737 MAX program;
- $600 million for aircraft storage, pilot training, and software updates; and,
- An estimated $500 million in settlements to victims' families.[90]

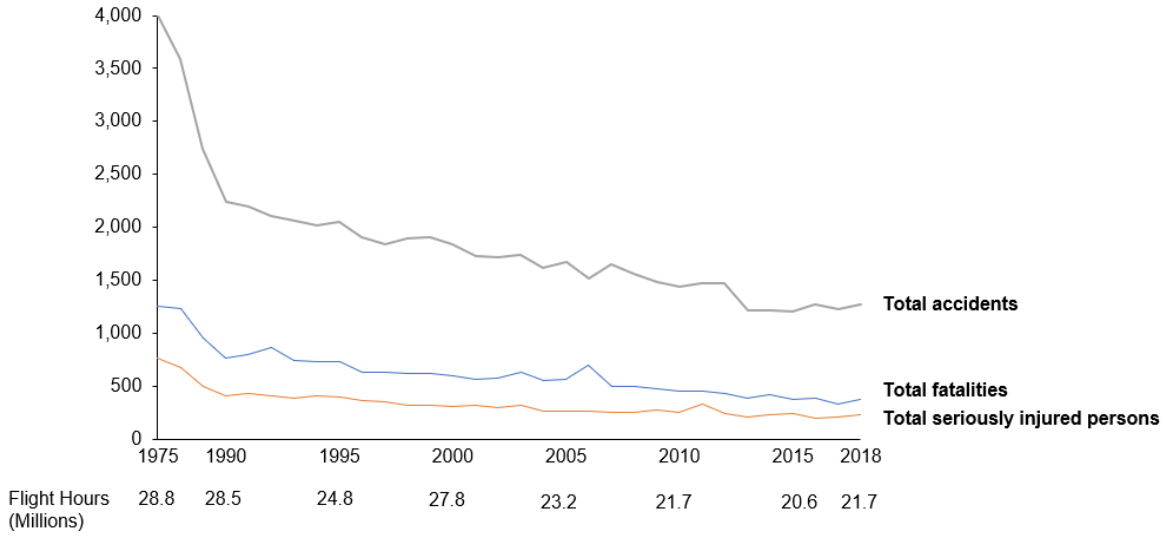
There were also indirect costs, including the costs of organizational changes, increased regulatory oversight, and higher capital costs due to downgrades in Boeing's debt ratings and drops in its stock price. Both Boeing and Airbus experienced sharp declines in their share prices once COVID-19 hit. Airbus's stock began to recover as people started to travel again in early 2021. But by mid August 2022, Boeing's shares were 52% below their level just before the first 737 MAX crash. Airbus shares were 20% higher (**Exhibit 12**).

Conclusion

By mid 2022, air traffic was rebounding and the outlook for the aircraft industry had turned up. Yet Boeing, the industry, the U.S., and other nations continued to face profound and challenging questions: How could the tragedies have been avoided? What prevented engineers and other Boeing employees from making their voices heard to managers who could have changed the course of the 737 MAX's design and development? Why did so many otherwise responsible employees and managers fail to stand up for quality and safety under the pressure to hit aggressive schedule and cost targets? Could Boeing, and other firms, be trusted to self-regulate? What reforms were needed at the FAA and other agencies to assure their independence and effectiveness? What ongoing oversight of the industry—and the regulators—would be needed?

Meanwhile, the families of the 346 victims continued to grieve.

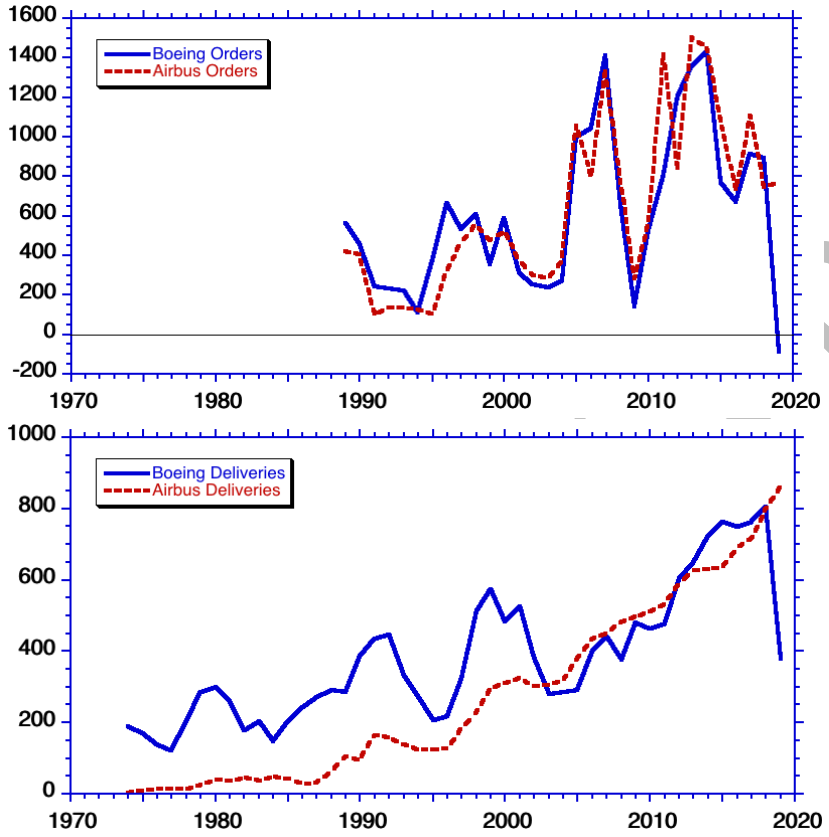
Exhibit 1 U.S. General Aviation Safety Data – 1975 to 2018



Note: Accidents on foreign soil and in foreign waters are excluded.

Source: Bureau of Transportation Statistics, "U.S. General Aviation Safety Data," https://www.bts.gov/content/U.S.-general-aviationa-safety-data.

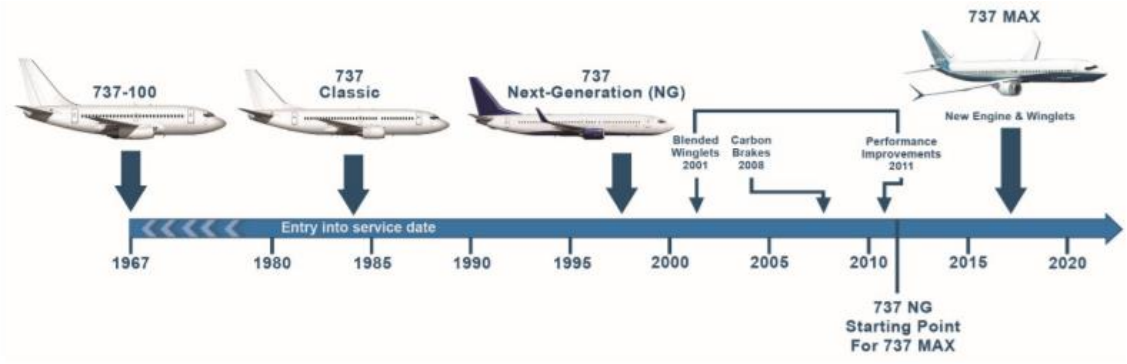
Exhibit 2 Commercial Aircraft Orders (top) and Deliveries (bottom) for Boeing and Airbus*



**Note: Data through 2019 (before COVID-19 pandemic impact).*

Source: Wikipedia, https://en.wikipedia.org/wiki/Competition_between_Airbus_and_Boeing#cite_note-Time_Period_Reports-107, accessed 24 October 2020. See also https://www.statista.com/statistics/264493/airbus-worldwide-aircraft-deliveries/ and https://www.statista.com/statistics/273968/number-of-delivered-aircraft-by-boeing/. All cite Boeing and Airbus as the underlying sources for the data.

Exhibit 3 Boeing 737 Family of Aircraft – 1967 to 2017



Source: U.S. Department of Transportation, Office of Inspector General, "Timeline of Activities Leading to the Certification of the Boeing 737 MAX 8 Aircraft and Actions Taken After the October 2018 Lion Air Accident," https://www.oig.dot.gov/sites/default/files/F.A.A.%20Oversight%20of%20Boeing%20737%20MAX%20Certification%20Timeline%20Final%20Report.pdf.

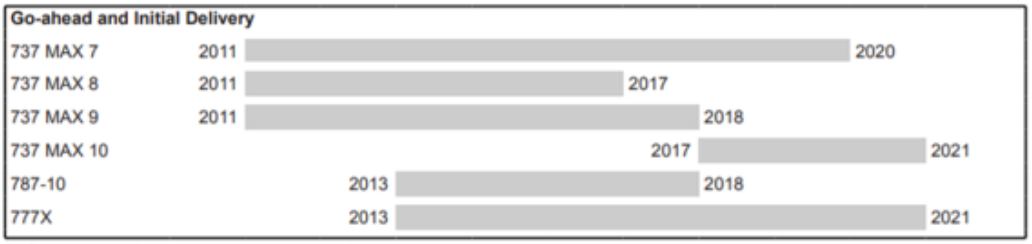
Exhibit 4 Boeing Aircraft Pricing Data

Average prices for Boeing aircraft as of March 2022, by type (in million U.S. dollars)	
737-700	89.10
737 MAX 7	99.70
737-800	106.10
737-900ER	112.60
737 MAX 8	121.60
737 MAX 200	124.80
737 MAX 9	128.90
737 MAX 10	134.90
767-300ER	217.90
767-300 Freighter	220.30
787-8	248.30
787-9	292.50
777-200ER	306.60
787-10	338.40
777-200LR	346.90
777 Freighter	352.30
777-300ER	375.50
777-8	410.20
747-8	418.40
747-8 Freighter	419.20
777-9	442.20

Source: Statista, "Airbus and Boeing," https://www.statista.com/statistics/273941/prices-of-boeing-aircraft-by-type/, accessed November 9, 2022. Originally sourced from www.boeing.com.

Exhibit 5 Boeing Commercial Airplanes "Go Ahead" and "Initial Delivery" Schedules

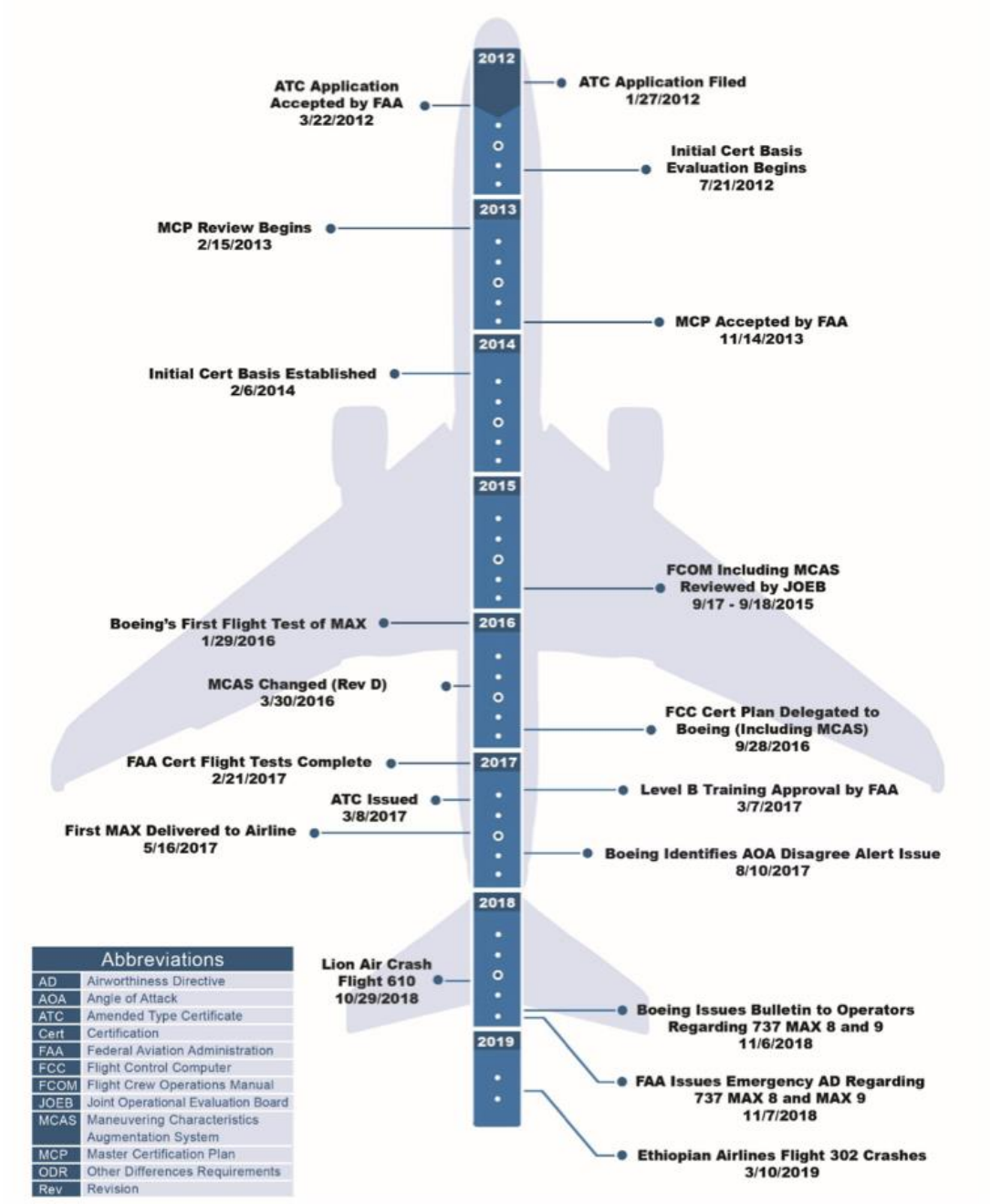
Program Development The following chart summarizes the time horizon between go-ahead and planned initial delivery for major Commercial Airplanes derivatives and programs.



Reflects models in development during 2019

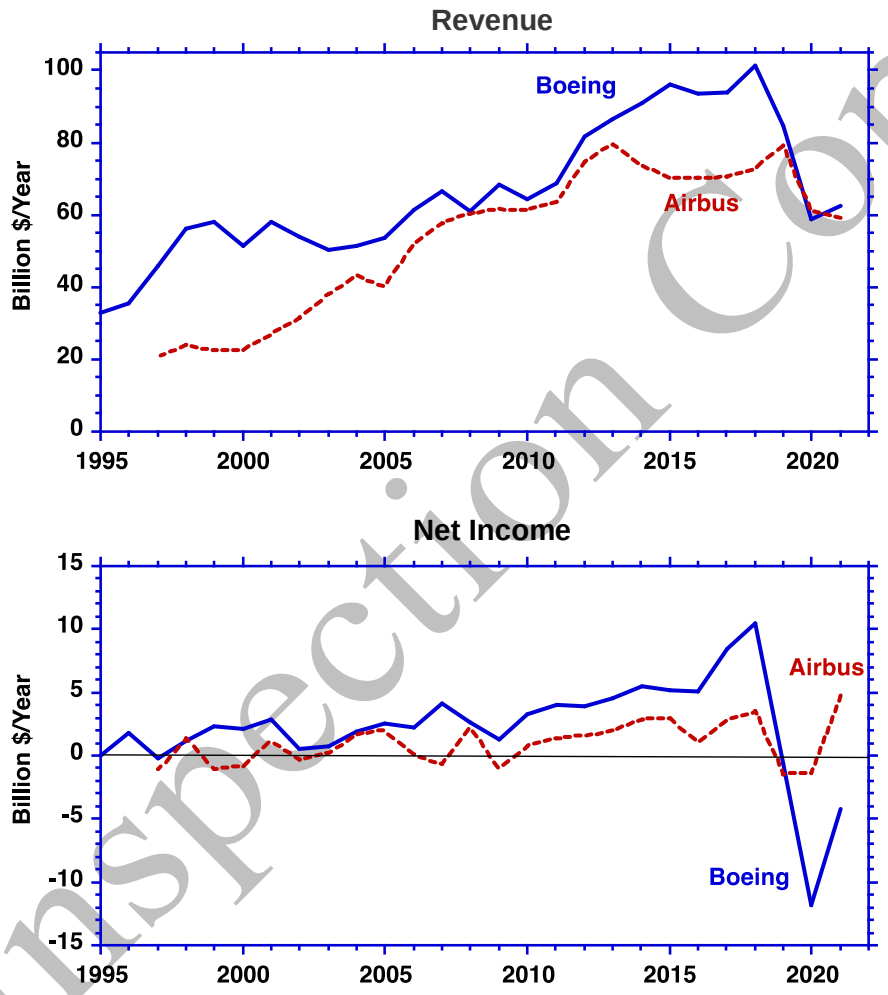
Source: Boeing Company 2019 Annual Report.

Exhibit 6 Timeline of Significant Events for the Certification of the Boeing 737 MAX 8



Source: U.S. Department of Transportation, Office of Inspector General, "Timeline of Activities Leading to the Certification of the Boeing 737 MAX 8 Aircraft and Actions Taken After the October 2018 Lion Air Accident," p. 11. https://www.oig.dot.gov/sites/default/files/F.A.A.%20Oversight%20of%20Boeing%20737%20MAX%20Certification%20Timeline%20Final%20Report.pdf.

Exhibit 7 Boeing and Airbus Revenue and Profit, 1995–2021

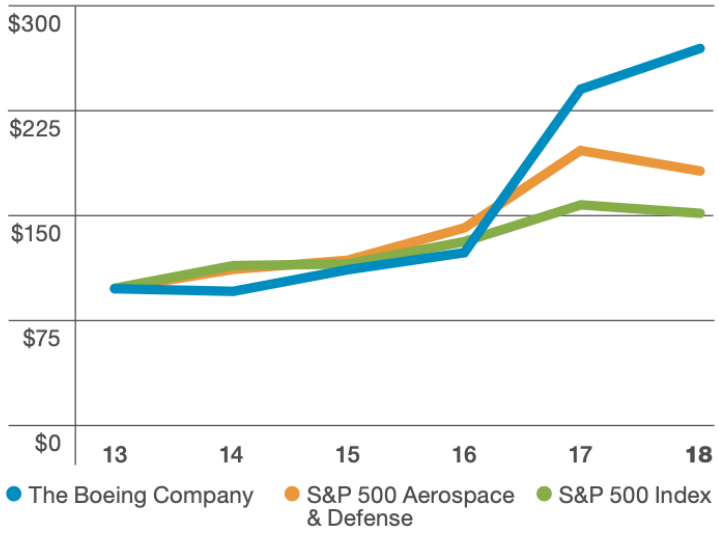


Source: Orbis.

Exhibit 8 ***Cumulative Five-Year Returns***

Company/Index	Base Period 2013	Years Ending December 2014	2015	2016	2017	**2018**
Boeing	100	97.47	111.17	123.75	241.03	**268.82**
S&P 500 Aerospace & Defense	100	111.43	117.49	139.70	197.50	**181.56**
S&P 500 Index	100	113.69	115.26	129.05	157.22	**150.33**

*Cumulative return assumes $100 invested; includes reinvestment of dividends.

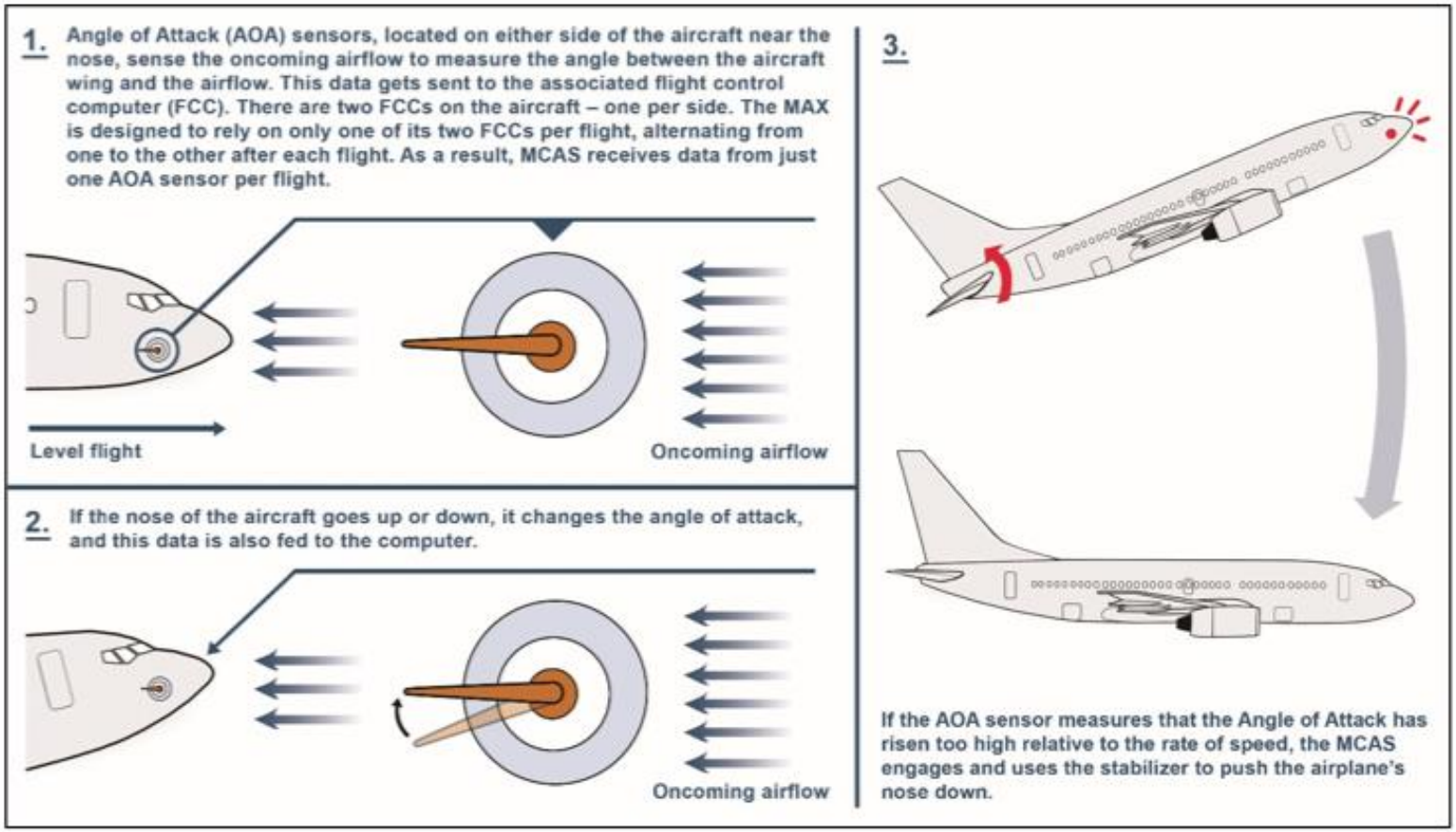


Source: Boeing 2018 Annual Report.

Exhibit 9 737 NG Engine (left) versus the 737 MAX Engine (right)

Source: U.S. Department of Transportation Inspector General Report, https://www.oig.dot.gov/sites/default/files/FAA%20Oversight%20of%20Boeing%20737%20MAX%20Certification%20Timeline%20Final%20Report.pdf, p. 6.

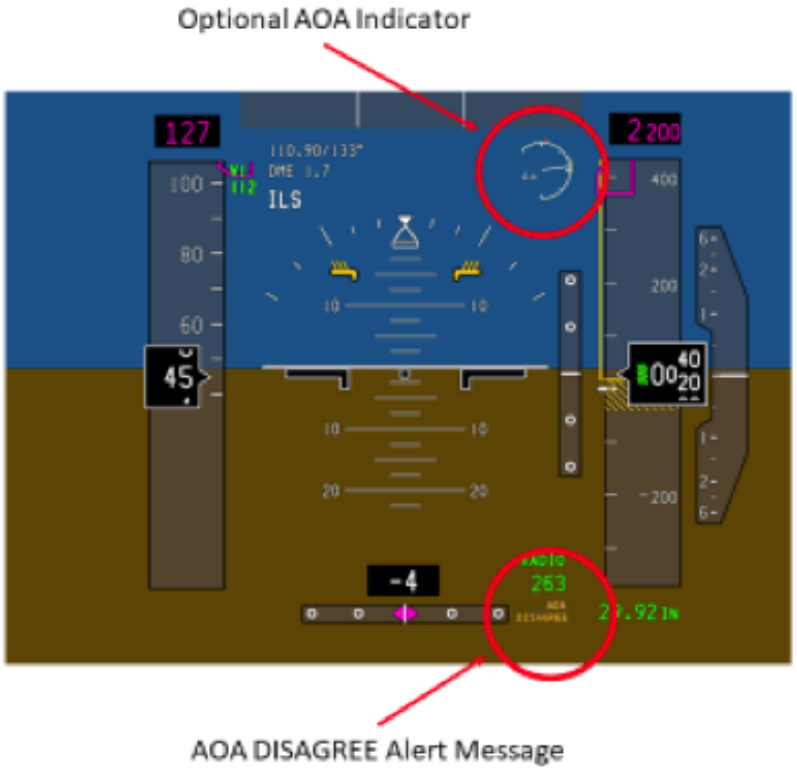
Exhibit 10 Overview of MCAS



Source: OIG analysis of FAA and Boeing data

Source: U.S. Department of Transportation Inspector General Report, https://www.oig.dot.gov/sites/default/files/FAA%20Oversight%20of%20Boeing%20737%20MAX%20Certification%20Timeline%20Final%20Report.pdf, p. 7.

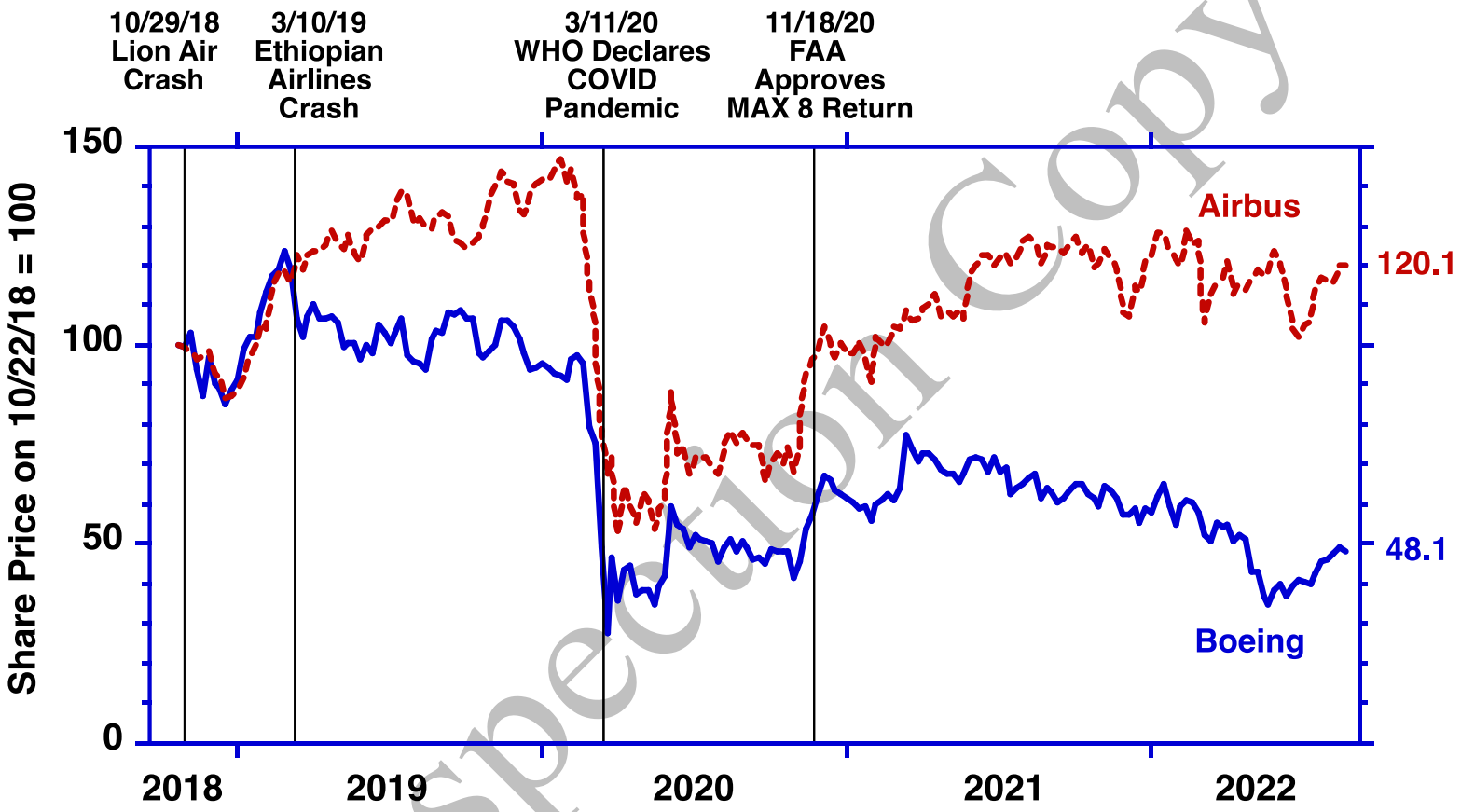
Exhibit 11 AOA Disagree Alert and AOA Indicator



Source: FAA

Source: U.S. Department of Transportation Inspector General Report, https://www.oig.dot.gov/sites/default/files/FAA%20Oversight%20of%20Boeing%20737%20MAX%20Certification%20Timeline%20Final%20Report.pdf, p. 28.

Exhibit 12 Boeing and Airbus Stock Prices



Index: Share prices on 10/22/2018 = 100.

Source: Data from Yahoo Finance. Weekly closing price, adjusted for splits, dividends, and capital gains distributions.

Endnotes

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[7] Ibid, p. 194.

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[10] Dominic Gates, "How Much Was Pilot Error a Factor in the Boeing 737 MAX Crashes?", *The Seattle Times*, May 15, 2019 (https://www.seattletimes.com/business/boeing-aerospace/how-much-was-pilot-error-a-factor-in-the-boeing-737-max-crashes/, accessed November 10, 2020).

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